sults were identified by the NYCTA Environmental Staff Division:

1. Even the basic existing summary of noise levels by routes and stations will allow the Division to readily respond to internal inquiries and to citizen complaints;
2. The tabulation of the treatment data base will provide an identification of options and a synthesis of the state of the art;
3. The actual operation of the PEACE program will allow evaluation of (a) past program efforts and (b) alternate future abatement scenarios; and
4. The actual operation of the PEACE program will allow scenarios proposed by any other party to be identified and will enable better information to exist when legislation, mandates, and regulations are considered.

In addition, the possible educational and training aspects of using the PEACE program on a specific property must be considered.

Other applications of the program system include the following.

1. An agency might use PEACE to explore sensitivities, namely what-if questions: What if a given benefit is -10 dB(A) and not -15 dB(A)? What if one action is taken rather than another?
2. An agency might use PEACE to determine whether a potential treatment would have major benefit to a system if it had its anticipated characteristics (or some lesser ones). Thus it could be used to assess candidate demonstration treatments.
3. Similarly, an agency can attempt to identify what characteristics a treatment should have, thus better directing its identification process.
4. PEACE can be used as a training tool in a deployment activity in addition to the other applications cited.

Certainly, further applications will be identified as user experience is gained.

ACKNOWLEDGMENT

The PEACE program system was developed with the benefit of substantial comments and interaction from the Environmental Staff Division of NYCTA. The contributions of A. Rafael and A. Paolillo are acknowledged with gratitude.

At the Transportation Systems Center of DOT, the encouragement and useful comments of R. Hinckley and C. Miller are acknowledged and appreciated.

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Effects of Parallel Highway Noise Barriers

J.J. HAJEK

The effects of opposing, parallel highway noise barriers have been analytically quantified by using principles of geometrical acoustics; they also have been compared with measured data. The evaluation was performed both for residential areas outside barrier walls and roadway areas between barrier walls. According to analytical results, the effect of parallel barriers can be substantial in residential areas. Under certain conditions the existing preconstruction sound levels can actually be increased (rather than reduced) by erecting vertical, sound-reflecting parallel barriers. However, direct field verification of the calculated results was difficult. In roadway areas the change of sound environment between parallel barriers could be verified by direct field measurements. The comparison of the measured and calculated results indicated that the method of using image sources to account for sound reflections is applicable for describing highway noise reverberation. It is postulated that this technique should also be applicable for estimating sound levels in residential areas. Results also suggest that the driver's perception of other vehicles on the road can be affected by parallel barriers.

The objective of the work reported in this paper was to obtain a better understanding of the effect of multiple reflections caused by parallel highway noise barriers. Opposing barriers, or highway cuts with retaining walls on both sides, can give rise to multiple reflections. The resulting reverberation field within barrier walls can significantly affect sound levels both within and outside (behind) barrier walls.

The Ontario Ministry of Transportation and Communications (MTC) has been retrofitting existing freeways with noise barriers since 1977. To date about 35 km of noise barriers have been built and about 60 percent of them are parallel to other barriers, thereby rendering the single-barrier situation atypical.

In spite of their frequency of occurrence, the treatment of parallel barriers is ambiguous. Although the role of multiple sound reflections between opposing barriers has been entirely discounted by some investigators (1), others have considered it to be highly significant (2). At any rate, the effect of parallel barriers has not yet become a part of common highway noise-prediction methods (3,4).

Parallel barriers can affect the sound environment in two distinct areas: (a) in the residential area outside barrier walls, and (b) in the roadway area within barrier walls. Both areas were investigated separately by using analytical methods based on geometrical acoustics and by direct field measurements.

RESIDENTIAL AREA

Analytical Investigation

A number of theories can be used to describe a reverberant field in enclosed or semienclosed spaces: wave-reflection theory, diffuse-field theory, and application of geometrical acoustics based on image theory. The geometrical acoustics method was used in this study because of its simplicity and reported reliability (5,6). To obtain a numerical solution, several assumptions were required.

1. Only specular reflection exists with no incident sound power scattering. Loss of sound energy because of reflections off the wall surfaces is acounted for by an absorption coefficient.
2. The absorption coefficient does not depend on angle of incidence (i.e., absorption coefficient is the same for all reflections) and is constant over the entire frequency range of highway noise that contributes significantly after A-weighting is applied.
3. The walls are high enough relative to source wavelength and the position of the source and the receiver aboveground to enable application of geometrical acoustics.
4. The contributions of real and image sources are added incoherently.
5. The source exhibits a uniform directivity pattern.

The frequency of the traffic noise source used in the analysis was 500 Hz because this frequency often dominates A-weighted traffic noise spectra. This choice allows the calculated sound levels to be considered as being in dB(A). The height of the source was assumed to be 1.5 m above the pavement surface, which corresponds to a highway traffic flow that contains about 10 percent trucks.

To include the effect of multiple reflections, a number of image roadways were constructed and included as input to a highway noise-prediction program STAMINA 1.0 (7). The program automatically accounts for distance attenuation (including atmospheric absorption) and barrier diffraction attenuation of sound emitted by the original as well as by the image roadways, thereby reducing the problem to a series of single-barrier situations. The method of constructing image sources (image roadways) is shown for the first two reflections in Figure 1.

Note that the program STAMINA 1.0 has been updated and reissued as STAMINA 2.0 (8). Nevertheless, none of the changes incorporated into STAMINA 2.0 (namely, the condition that the loss of excess ground attenuation from the erection of a barrier must not exceed barrier diffraction loss) affects the reported results. In other words, STAMINA 2.0 results would be the same as those obtained by STAMINA 1.0.

The number of reflected waves originating from image sources that can reach a receiver depends on the receiver location, the relative heights of the opposing barriers, and the source height. Although an infinite number of reflections exist for receivers located in the region below the barrier top ($h_r < h_b$ in Figure 1), provided that the far wall--the wall farthest from the receiver--is equal to or higher than the near wall, only the first 15 images were included in the analysis for practical purposes.

The effect of the number of reflections (image sources) included in the analysis is shown in Figure 2 for a barrier geometry used subsequently for more detailed analysis. The parallel barrier degradation shown on the ordinate of Figure 2 is the reduction in the single-barrier insertion loss because of the presence of the opposite barrier. Ground cover is considered to be acoustically hard. According to the data in Figure 2, the degradation asymptotically increases as more reflections are accounted for and as the distance from the barrier increases. The contribution of the omitted reflections (reflections 16 to infinity) to the parallel barrier degradation was found to be smaller than 10 percent of the contribution provided by the first 15 reflections. This applied even for highly reflective barrier surfaces and for large distances behind the barrier.

The number of reflections used in the analysis of receivers located above the barrier top ($h_r > h_b$) ranged from 0 to 15. To be included in the calculation, the reflected wave must have reached the opposite barrier at least 0.6 m below the barrier top, which corresponds roughly to the wavelength of the 500-Hz source. This is a conservative assumption to account for the effect of barrier edge where a part of the sound energy is diffracted and scattered over the top of the opposite barrier.

The reflected waves are also attenuated by absorption of barrier surfaces. For the image sources, the original sound power of the source was reduced in proportion to the cumulative multiple-reflection coefficient α_M, which is defined as follows: $\alpha_M = (1 - \alpha)^j$, where α is the simple absorption coefficient (assumed identical for both barrier surfaces), and j is the number of reflections.

Results

The degradation effect of parallel barriers is shown in Figure 3 by using attenuation contours developed for 4.5-m-high barriers that are 36.5 m apart. The insert in Figure 2 shows a cross-section sketch of the barriers. This example may correspond to a six-lane freeway situated on flat terrain. The sound-absorption coefficient of barrier surfaces was assumed to be 0.05; i.e., the barriers were reflective. The contours in Figure 3 were developed for

Figure 1. Construction of image sources.

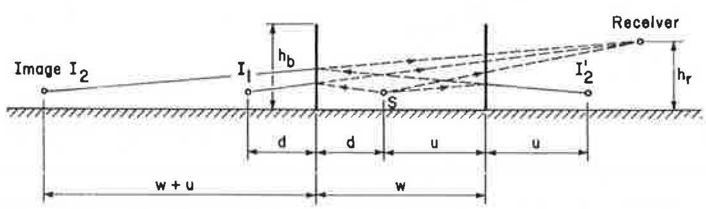
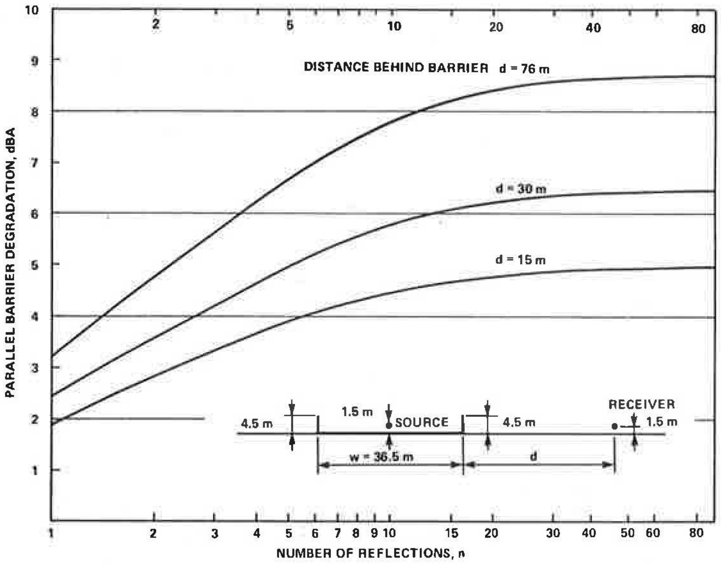
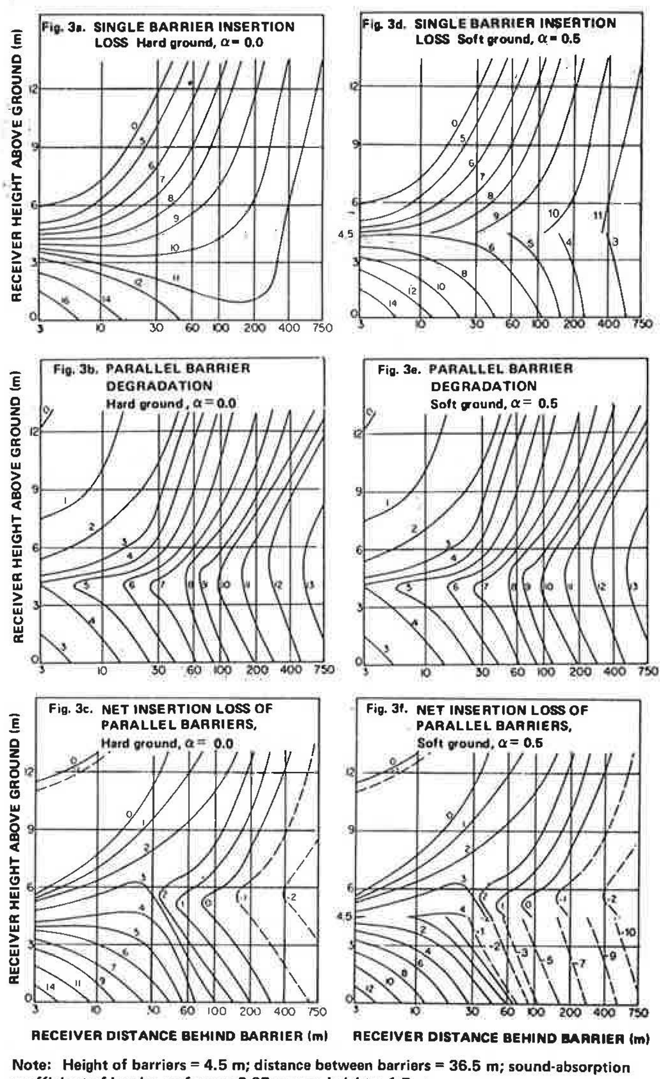


Figure 2. Parallel barrier degradation versus number of reflections.



Note: Height of barriers = 4.5 m; distance between barriers, w = 36.5 m; receiver is 1.5 m above the ground plane and distance d behind the barrier; sound-absorption coefficient of barrier surfaces, α = 0.05.

Figure 3. Barrier attenuation contours [dB(A)], showing the effect of parallel barriers.



Note: Height of barriers = 4.5 m; distance between barriers = 36.5 m; sound-absorption coefficient of barrier surfaces = 0.05; source height = 1.5 m.

two ground cover types between the highway and the receivers:

1. Acoustically soft, absorptive ground--α = 0.5 [α is defined in the FHWA model (3)], which corresponds to the before-barrier sound-attenuation rate of approximately 4.5 dB(A) per distance doubling; and
2. Acoustically hard ground--α = 0.0, which corresponds to the before-barrier attenuation rate of 3.0 dB(A) per distance doubling; when the barrier is in place, the program STAMINA 1.0 assumes an attenuation rate of 3.0 dB(A) per distance doubling, regardless of the prebarrier ground type, because of the apparent shift of the noise source to the top of the barrier (as discussed previously, the same assumption would be used by STAMINA 2.0 because the barrier diffraction attenuation exceeded the excess ground attenuation).

For each ground type, isodecibel contours show (a) the single-barrier field insertion loss [Δs (Figures 3a and d)]; (b) its degradation because of the erection of the opposite barrier [Δd (Figures 3b and e)]; and (c) the net field insertion loss for a parallel barrier situation [Δs - Δd (Figures 3c and f)].

Although the isodecibel lines that show the insertion loss of a single barrier on the hard ground (Figure 3a) are smooth, the corresponding lines for a single barrier on soft ground (Figure 3d) exhibit a distinct discontinuity for receivers 4.5 m aboveground. This is the result of the recommendation in the FHWA model (3) that hard ground be used (α = 0) whenever the line of sight (a direct line between the noise source and the receiver) averages more than 3 m aboveground. Considering the source height of 1.5 m, the switch from the hard to the soft ground occurs at the receiver height of 4.5 m. Consequently, Figures 3a and d are identical for all receivers more than 4.5 m aboveground.

The assumed change in ground attenuation whenever the average propagation height exceeds 3 m results in a considerable jump in the insertion loss. For example, according to the data in Figure 3d, a 3-dB(A) insertion-loss contour is changed, at the height of 4.5 m, into an approximately 11-dB(A) contour. It has been proposed to replace the abrupt change in the excess ground attenuation at the 3-m height by a more gradual function that incorporates both the height aboveground and the distance between the source and the receiver (4,9).

Note that the parallel barrier degradation shown in Figures 3b and e is independent of the ground cover behind the barriers. Thus Figures 3b and e are identical.

The predicted degradation of the single-barrier attenuation from the erection of the opposite barrier is quite dramatic, particularly when the ground between the highway and the observer is absorptive. For example, the data in Figure 3f indicate that no net insertion loss is produced by the 4.5-m-high reflective barriers for receivers approximately 50 m behind the barrier at 1.5 m aboveground. Furthermore, at a distance of approximately 200 m behind the barrier at 1.5 m aboveground, the net field insertion loss is negative, which indicates a predicted increase of about 6 dB(A) over the condition with no barriers. The net insertion loss of the reflective parallel barriers situated on hard ground (Figure 3c) is equally affected by the presence of the opposite barrier. However, the net insertion loss is considerably higher than for the barriers on soft ground because of the higher single-barrier insertion loss. Nevertheless, Figure 3c indicates no net insertion loss for receivers approximately 300 m behind the barrier at 1.5 m aboveground.

It should be pointed out that the degradation effect of opposite barriers can be considerably reduced or eliminated by using barriers with sound-absorptive surfaces or by inclining barrier surfaces by 3° to 10° away from the highway (10).

Field Measurements

Even though the potential degradation effect of reflective parallel barriers is considerable, it is still difficult to verify the degradation by direct field measurements. The degradation effect of parallel barriers increases with distance (Figure 2). However, at larger distances behind the barrier, where the degradation effect reaches measurable proportions (i.e., 3 or 4 dB), sound levels are usually quite low [often in the 55 to 60 dB(A) range] and can easily be influenced by highly variable community noise sources (such as local traffic or children playing) and by weather-related factors (such as wind speed and direction).

In recent studies in which the field acoustical performance of parallel highway noise barriers was evaluated (11-13), it was found that the effect of parallel barriers may not be as significant as the application of geometrical acoustics would suggest. This has been attributed to various causes, namely,

1. The presence of large reflecting surfaces at these sites (houses, parapet walls, highway vehicles) before as well as after barrier construction;
2. Relatively low barrier height at certain locations (about 3 m) and large distances between them; and
3. Difficulties in accurately measuring insertion losses when sound levels are also influenced by community noise.

Thus more carefully designed and executed field studies are required.

ROADWAY AREA

The sound field between barrier walls can be assessed more easily than sound levels in residential areas. The influence of community noise sources and reflective surfaces from outside the barrier walls is insignificant. Analytical modeling is simplified, and calculated results can be readily verified by simultaneous measurements of sound levels at a location between walls and at a corresponding location without walls. The understanding of the sound environment between barrier walls enables (a) better understanding of the sound field behind barrier walls where residences are located, (b) evaluation of the reverberant sound field between walls as it affects driver perception of other vehicles on the roadway, and (c) assessment of design variables such as sound-absorptive treatment and wall geometry.

Analytical Investigation

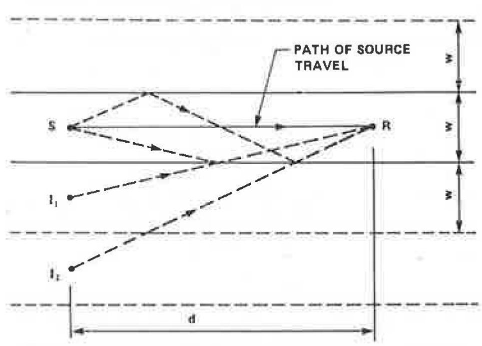
Analytical evaluation of the sound environment in the roadway area (between barrier walls) was based on the same method and assumptions as those used for the residential area (i.e., geometrical acoustics, source frequency of 500 Hz). Also, the effect of sound scattering and the resulting diffuse field were not included in the analyses. Their contribution to the multiple-reflection field formed by plain walls, the height of which is considerably smaller than the distance between them, would be negligible (14).

As shown in Figure 4, the walled highway was represented as a channel between two infinite sound-reflecting planes. In the center of the channel is a single point source (S), which emits sound energy at a constant rate and frequency spectrum. Sound waves can reach a receiver (R) both directly and after one or more reflections off side walls. These reflections can be represented by two infinite sets of image sources, each situated on one side of the channel. The space within the channel is referred to as the reverberant field. The corresponding space not bounded by the channel walls is referred to as the free field.

The objective of the mathematical model was to obtain a difference between the free-field and reverberant-field sound levels. For this reason, several factors that affect only the total sound energy or its time variation, but do not affect the difference between sound energy in the reverberation and free fields, were not included in the model. These factors are

1. Contributions from pavement (ground plane) reflections [the omission of pavement reflections is considered negligible because the pavement reflections would exist in both fields; a perfectly sound-absorbing ground was assumed in the subsequent calculations; therefore the same results (i.e., difference between the two fields) would be obtained for a perfectly reflecting ground];

Figure 4. Construction of image sources.



Note: Image sources exist in two discrete pairs, e.g., I_2 = image source for the second reflection and the first pair, and w = distance between walls; d = distance from source to observer.

2. The effect of the source motion on the sound radiation [an excellent discussion of this topic can be found in Lansing (15)]; and

3. Effect of retarded time, i.e., time at which the observed sound was emitted by the source (sounds traveling on different propagational paths would not reach the receiver simultaneously; however, the total sound energy reaching the receiver over a period of time is not affected).

The total sound intensity at the receiver (Itot) can be obtained by adding sound intensity reaching the observer directly (Iff) and sound intensity reaching the observer after one or more reflections (Irev). The increase in sound intensity level (ΔL) caused by reflections can be expressed as

$$\Delta L = 10 \log (\mathrm{Itot}/\mathrm{Iff}) \tag{1}$$

where ΔL is the difference between total sound intensity and free-field sound intensity (dB); and Itot is the total sound intensity (watts/m^2); i.e., Itot = Iff + Irev, as previously defined.

Equation 1 was expanded and modified to include an infinite number of reflections that exist for the configuration of Figure 4 and to include sound attenuation due to atmospheric absorption. Assuming spherical spreading and a perfectly absorbing ground, the following equation (16) is derived:

$$\Delta L = 10 \log \left(1 + 2d^2\, 10^{Ed} \sum_{n=1}^{\infty} \left\{ (1-\alpha)^n / [d^2 + (nw)^2] \right\} \cdot [1/10^{E} \sqrt{d^2 + (nw)^2}] \right) \tag{2}$$

where

- d = straight-line path length between the source and the receiver (m),
- E = atmospheric absorption coefficient (0.001 772 dB/m),
- n = number of reflections (n = 0,1,2,3...),
- α = sound-absorption coefficient (identical for both barrier surfaces), and
- w = distance between parallel walls.

Mathematical Modeling

It is assumed in Equation 2 that the source and the receiver are located on the path the source travels. However, for short distances between the source and the receiver, Itot depends on the position of source and receiver in relation to boundaries. For this reason, Equation 2 was modified to distinguish the receiver location from the source path (see Figure 5), and the numerical solution was computerized.

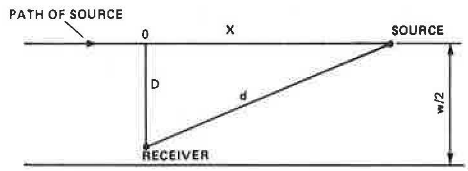
Typical single-point source passby curves calculated for the free field and for the reverberation field are shown in Figure 6. In the case of the reverberation field, the distance between the two barrier walls was 30 and 60 m. Also shown is the effect of atmospheric absorption, which becomes noticeable only for greater distances from the source.

The difference between sound levels in the reverberation and free fields is independent of the sound power of the single-point source (Equation 2). Moreover, it is also independent of the number of single-point sources, provided that their number, intensity, and position relative to the walls are the same for both fields. Thus, by integrating the sound energy of the single-point source passby curves in the reverberant and free fields, and then calculating the difference between them, the difference in sound energy between the two fields for the total traffic flow (ΔL_{eq}) can be obtained.

The difference between sound energy levels in the reverberation and free fields (ΔL_{eq}) was evaluated over an integral of distance rather than time (16). Thus the influence of the width as well as length of the reverberation field could be directly quantified.

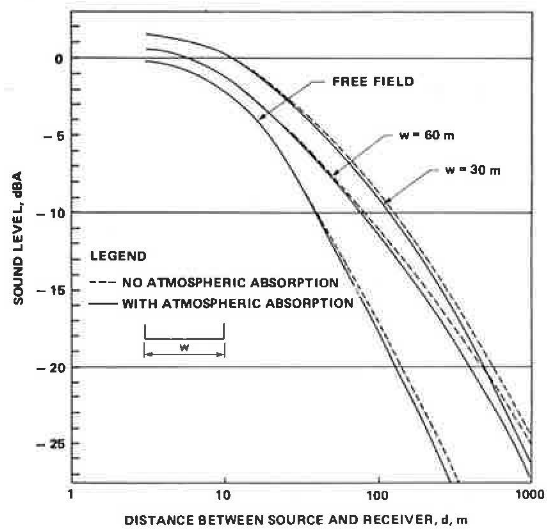
Some of the results are shown in Figure 7, which relates L_{eq} to the distance between walls and to the sound-absorption coefficient of the walls. It is apparent that the sound-absorption coefficient

Figure 5. Parameters for calculating passby curves.



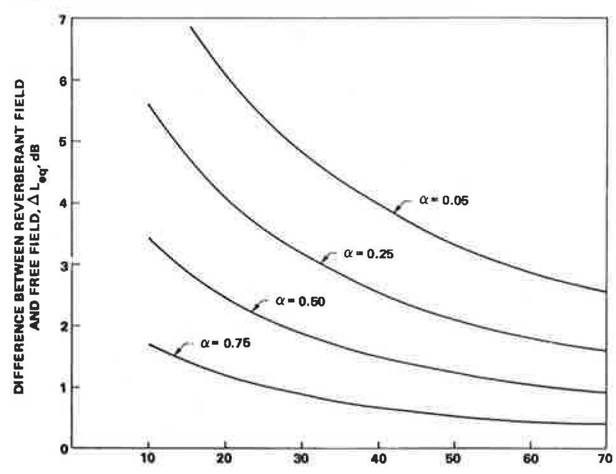
Note: D = distance of closest approach, d = actual path length distance between source and receiver.

Figure 6. Single-point source passby curves.



Note: Absorption coefficient of walls, α = 0.05; distance to closest approach, D = 13.0 m; number of reflections accounted for, n = 15; coefficient of atmospheric absorption, E = 0.001 772 dB/m.

Figure 7. Increase of sound levels in reverberation field.



Note: Sound-absorption coefficient of walls (α) varies; distance to closest approach, D = 13.0 m; number of reflections accounted for, n = 15; coefficient of atmospheric absorption, E = 0.001 772 dB/m; length of reverberation field, X = 1500 m.

(α) is an important parameter that influences sound energy build-up within walls. For example, ΔL_{eq} for partly sound-absorbing walls (α = 0.5) at 10 m apart is similar to ΔL_{eq} for sound-reflective walls (α = 0.05) at 50 m apart. The sound energy build-up within walls can also influence sound levels outside of them, or behind barrier walls or retaining walls.

Experimental Results

To verify the mathematical model, two types of full-sized experiments were conducted: (a) measurements of passby curves of single vehicles, and (b) measurements of total highway traffic flow.

Comparison of Passby Curves of Single Vehicles

Passby curves of single vehicles were measured along a relatively flat six-lane freeway (Highway 409) by using two heavy diesel trucks. The trucks passed by two adjacent receivers at a constant speed of 80 km/h; the first receiver was located within a reverberation field formed by two 6-m-high retaining walls approximately 1500 m long, and the second receiver was located in a free field with no reflecting surfaces, such as houses or parked vehicles, within a 90-m radius. The retaining walls were of untreated concrete with a coefficient of absorption (α) estimated at 0.05. A schematic diagram of the experimental setup, including a cross section of the reverberant field, is shown in Figure 8.

Measured time histories for both free and reverberant fields are compared with calculated time histories for a typical passby test in Figure 9. The measured sound levels in this figure are dB(A) levels; the calculated sound levels are for a frequency of 500 Hz. The data in Figure 9 indicate extremely close agreement between the measured and calculated time histories, disregarding considerable fluctuations of measured values. The fluctuations are a result of ground interference, wall scattering, turbulence, and other factors that were not included in the model.

In addition to the time histories, which are somewhat difficult to evaluate because of instantaneous fluctuations, maximum sound levels were also evaluated. The average measured difference between maximum sound levels emitted by the test trucks in the reverberation and free fields was 4.8 dB(A). The corresponding calculated difference was 3.3 dB(A).

Comparison of Total Traffic Flow

Experimental measurements of the total traffic flow were conducted on the same site along a six-lane freeway (see Figure 8), and on an additional site along an eight-lane freeway [Queen Elizabeth Way (QEW)], by using a procedure similar to that used for the single-vehicle measurements. The length of the reverberation field at the QEW site was approximately 400 m. Two microphones were used simultaneously--one located within a reverberation field and the second in a free field. Traffic flow volume, composition, and speed; pavement type; distance between receiver and traffic lanes; and other factors were identical at both locations. Consequently, the difference between the sound levels obtained at the two locations could be attributed solely to the effect of parallel reflecting walls.

Results were expressed by the highway traffic noise descriptors L_{eq}, L_{10} (sound level exceeded 10 percent of the time), L_{50}, and L_{90}. Results for the six-lane freeway are given in Table 1.

The data in Table 1 indicate that noise descriptors related mainly to peak sound levels (L_{10} and L_{eq}) are not as affected by the reverberation field as noise descriptors related mainly to average and background sound levels (L_{50} and L_{90}, respectively).

For example, the difference between the reverberant and free fields was about 3 dB(A) in terms of L_{eq} levels, whereas the corresponding difference in terms of L_{90} levels was about 8 dB(A). This is not surprising, considering the passby curves shown in Figures 6 and 9. For a single-vehicle passby, the difference between sound levels in the reverberant and free fields increases with the distance

Figure 8. Schematic diagram of measurement setup, Highway 409.

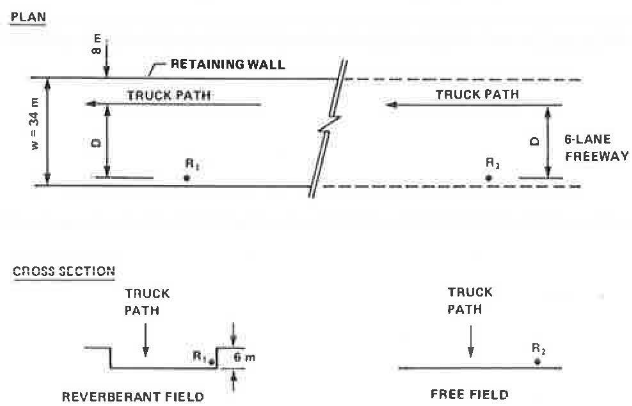
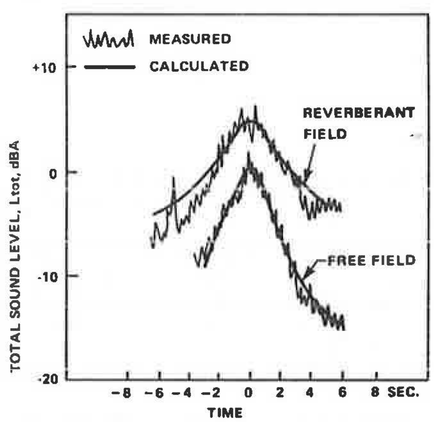


Figure 9. Comparison of measured and calculated passby curves.



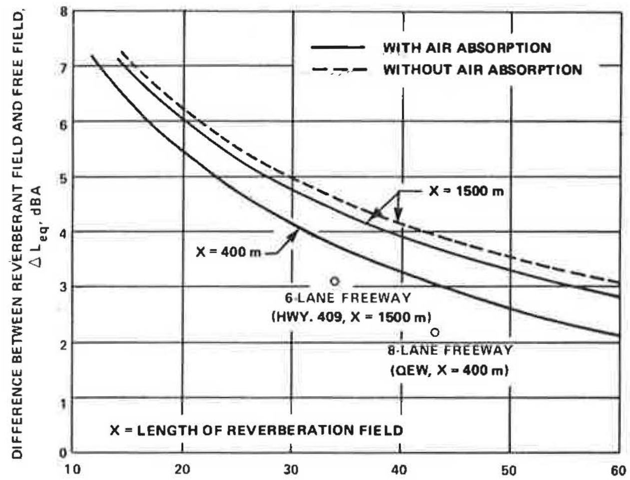
Note: Conditions are as follows: speed of test vehicle = 80 km/h; distance to closest approach, D = 24.7 m; number of reflections accounted for, n = 15; coefficient of atmospheric absorption, E = 0.001 772 dB/m; length of reverberation field = 1500 m, and its width, w = 34 m; sound-absorption coefficient of walls, α = 0.05.

Table 1. Comparison of sound environment measured in reverberation and free fields, Highway 409.

Item	Sound Descriptor			
	L_{eq}	L_{10}	L_{50}	L_{90}
No. of measurements[a]	11	11	11	11
Avg difference between reverberation field and free field [dB(A)]	3.07	4.44	6.74	8.32
Standard deviation of differences between reverberation field and free field [dB(A)]	1.32	1.23	1.35	1.52

[a]All measurements were 20 min in duration on Highway 409.

Figure 10. Comparison of measured and calculated differences between reverberant and free fields.



Note: Calculations based on sound-absorption coefficient of walls, α = 0.05; distance to closest approach, D = 13.0 m; number of reflections accounted for, n = 15; coefficient of atmospheric absorption, E = 0.001 772 dB/m.

between the source and the receiver. This tends to affect background levels more than peak levels.

The changes in the reverberant sound field cannot be characterized only by an average increase in sound levels. The time distribution of sound levels is also changed because peaks and background levels are increased at different rates. This is important when considering a driver's perception of other vehicles on the road. When the peak sound levels of individual vehicles are increased, they may be perceived by a driver as being closer than they actually are. However, the increase in the peak level is masked by an even higher increase in the background levels. Thus the driver's hearing perception of the distances between vehicles on the road is affected. The actual perception of the driver depends also on the sound levels emitted by the driver's own vehicle, its sound insulation characteristics, the density and composition of traffic flow, and other variables.

The calculated and measured differences between sound levels in the reverberant and free fields for the two freeways are compared in Figure 10. The comparison is in terms of L_{eq} levels. The measured differences are lower than the calculated ones by about 1 or 2 dB(A). Considering approximations and assumptions used in the mathematical model, this is quite a reasonable agreement. Discrepancies could arise, for example, from a nonuniform directivity pattern of highway vehicles, shielding by highway vehicles, the reflection-scattering process, and experimenal error.

CONCLUSIONS

The case of parallel highway noise barriers may actually represent a typical case of barrier arrangement because, at least in Ontario, noise-sensitive land uses exist more often on both sides of expressways rather than on a single side only. Nevertheless, the effects of parallel barriers are not as well understood as those of single barriers. The following conclusions are drawn.

1. According to analytical results, the impact of parallel barriers on the residential area can be substantial and can result in higher sound levels for a parallel barrier installation than for a free-field situation. This is particularly pronounced in the case of barriers situated on an acoustically soft ground.
2. Field measurements revealed little effect from parallel barriers. It was hypothesized that the presence of large reflecting surfaces such as houses (both before and after barrier construction) can mask the degradation effect of erecting additional reflecting surfaces (i.e., barriers). This, together with the influence of community noise sources and weather-related factors, makes field verification of the degradation effect difficult.
3. In the roadway area (within barrier walls), a close agreement was obtained between predicted and measured sound levels. Predictions were based on geometrical acoustics that used image sources to account for multiple reflections; these predictions could be verified by field measurements.
4. Because the image-source theory provides reliable results for the sound field within barrier walls, it is postulated that it may also provide reliable results when applied to the sound field outside the walls in the residential area, where verification by direct field measurements is difficult.
5. In the roadway area the background sound levels are significantly increased because of multiple reflections. This can affect the drivers' perception of distances between vehicles on the road.
6. In view of the potential extent of parallel barrier installations and their effects, research should be continued, with emphasis on full-scale testing.

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IMAGE-3: Computer-Aided Design for Parallel Highway Noise Barriers

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Although most state transportation agencies in the United States have constructed traffic noise barriers on new or existing highways, little attention has been given to the problem of multiple reflections between parallel barriers. That is, when barriers are on both sides of a highway, each barrier degrades the other's performance. Therefore, the money spent on the noise-abatement project may not bring the expected benefits that were sought. In other countries, especially in Japan, use of barriers with sound-absorptive faces to counteract this problem is commonplace. Much of this other multiple-reflections analysis and absorptive treatment design has been done through acoustic scale modeling. This technique, when correctly used, is generally beyond the resources of almost all U.S. transportation agencies. There has been no versatile, easy-to-use, parallel barrier analysis and design tool for American designers. The only currently available FHWA procedure, a nomograph, has many constraints that limit its usefulness. Because of a need to consider absorptive treatment for I-440 in Nashville, Vanderbilt University has developed an algorithm and computer program called IMAGE-3 for the analysis of parallel barriers. The algorithm combines the emission, propagation, and diffraction components of the FHWA traffic noise prediction model with geometrical acoustics for addressing the multiple-reflection phenomenon. The program overcomes the constraints of the parallel barrier nomograph and permits quick analysis of many situations, including different sound-absorption schemes.

Nearly 200 miles of traffic noise barriers had been constructed by state transportation agencies in the United States as of the end of 1980 (1). This total may well represent only a fraction of the total U.S. barrier program, because in 1979 the FHWA estimated that there were potentially more than 875 miles of barrier projects on the Interstate highway system (2). Much of the existing mileage and most of the potential future mileage are in urban areas, where noise barriers are often required on both sides of the highway. (This will be referred to as a parallel barrier situation.)

Theoretical and scale-modeling studies indicate that the acoustic performance of each barrier can be seriously degraded by the presence of the other wall, to the point where no noise reduction occurs, or the levels actually increase over the no-barrier condition (3-7, and paper by Hajek elsewhere in this Record). Simply put, multiple reflections reduce or eliminate insertion loss.

If unaddressed this phenomenon can have serious consequences on an agency's noise-abatement program. First, scarce financial resources are being improperly spent; each noise barrier will not reduce community noise levels as anticipated. Second, the agency will not be providing the degree of noise reduction promised to a community to meet federal regulations. [Note that abatement design criteria are given by the FHWA (8).] As a result, the agency may lose its credibility with the public. In addition, agency decision makers may lose faith in noise barriers as legitimate means for making highways compatible with their environs.

The parallel barrier multiple-reflections problem has received increasing recognition and study during the past several years. The typically mentioned method to minimize the multiple-reflection problem is the treatment of one or both of the barrier surfaces facing the highway with sound-absorbing material (4,7,9). However, only one American parallel noise-barrier project has been constructed by using such materials to reduce the multiple-reflection phenomenon (10). Other studies have suggested tilting barriers back by 10° to redirect reflection (7,9).

There are several reasons for the general lack of consideration of the parallel barrier problem nationwide.

1. Most noise-barrier acoustical designs are performed by using computer programs (11-14). Despite recent FHWA emphasis on parallel barrier analysis (7,15), none of these programs can correctly analyze such a situation. The only available tool is a nomograph (7), which is severely limited in its applicability to real-world design problems.
2. Most American noise-barrier designers were trained through an early FHWA noise-fundamentals course (16) that concentrated on single-wall analysis and design. Even in an advanced training course, first taught in late 1982, single-wall analysis was emphasized (17). [Designers, however, did receive a brief introduction to the parallel barrier nomograph during workshops for the FHWA demonstration project on highway noise analysis (15).]